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Objective cyclone climatologies of the North Atlantic – a comparison between the ECMWF and NCEP Reanalyses

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Abstract Simple and easily reproducible techniques have been used to construct two objective cyclone climatologies of the North Atlantic-European sector. The goal of this study is to increase understanding of cyclones with the potential to cause damage, in particular, those reaching Beaufort category 7 and above. The two climatologies constructed here span the period 1979–2000 and have been developed from reanalysis mean sea level pressure data from the ECMWF (European Centre for Medium Range Weather Forecasts) and NCEP (National Centres for Environmental Prediction). The ECMWF reanalysis data are only available for 15 years, and have been extended from 1994 using operational analyses. The major temporal and spatial characteristics of North Atlantic cyclones are examined and a comparison between the climatologies developed from the two data sets is carried out. The well-known cyclogenesis regions along the east coast of the United States and to the southeast of Greenland are replicated by both reanalyses, as is the characteristic southwest/northeast orientation of the dominant cyclone track across the Atlantic basin. However, only weak correlations are found between the time series of cyclone frequency produced from the two reanalyses, and this is particularly true for the lower intensity Beaufort Scale category 0–6 cyclones. This result, together with the large differences in the spatial distribution of cyclones over Greenland for Beaufort Scale 0–6 cyclones, indicates the NCEP reanalyses generates fewer systems than the ECMWF reanalyses. The overall conclusion is that the ECMWF mean sea level pressure data produce a more comprehensive climatology of North Atlantic cyclones at all scales.

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1 Introduction

The main aim of this study is to construct and compare two objective cyclone climatologies for the North Atlantic-European sector. The goal of this study is to increase understanding of cyclones with the potential to cause damage, in particular, those reaching Beaufort category 7 and above. The climatologies are derived from the output of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centres for Environmental Prediction (NCEP) state-of-the-art reanalysis systems. Mean sea level pressure reanalysis data are used, together with a simple, easily reproducible methodology to create the climatologies. In the past, climatologies have been developed from one of the two reanalyses (Blender et al. 1997; Trigo et al. 1999, 2000; Gulev et al. 2001, Hoskins and Hodges 2002) but to date only one comparison has been made of the cyclone climatologies developed from the two reanalysis data sets (Hodges et al. 2003).

The study of the climatology of cyclones in extra-tropical latitudes has always been an area of great interest to climatologists. One of the earliest analyses was carried out by Furley in 1884 (reported by Ballenzweig 1959). The research method remained fairly consistent over time until recently, when the use of computers has enabled more sophisticated analyses to be undertaken. Up until the mid-1980s, manual methods for developing cyclone climatologies were used, inspecting individual synoptic charts and recording the characteristics, for example location and central pressure, of each identified cyclone e.g. Colucci (1976) and Schinke (1993). Studies based on the manual analysis of charts of cyclone tracks compiled for example by *Monthly Weather Review* include those of Hosler and

Gamage (1956), Hayden (1981a), and Agee (1991). More recently, automated tracking schemes have been developed based on gridded data sets from observations or reanalysis simulations, in order to produce objective descriptions of cyclone behaviour.

Haak and Ulbrich (1996) used an automated detection and tracking scheme based on ECMWF 1000 hPa geopotential height reanalysis data, on a grid interpolated from 3° × 3° to 0.3° × 0.3°, to investigate the behaviour of cyclones over the North Atlantic for the 1980–1993 period. They carried out a verification of their automated system by comparing it to output from Schinke's (1993) manual study, which utilised historical weather maps. In general, the objective method was found to be reliable. Blender et al. (1997) used high resolution (6-hourly and 1.1° × 1.1° latitude/longitude grid) ECMWF 1000 hPa geopotential height data for the period 1990–1994 and the months November to March. The study area covered the North Atlantic region, 80°W–30°E and 30°N–80°N. Trigo et al. (1999) used similar techniques but focused instead on the Mediterranean region. Trigo et al. (2000) used NCEP reanalysis data to investigate cyclone activity across the North Atlantic, as did Gulev et al. (2001).

Automated detection and tracking schemes have become progressively more elaborate over the past decade ranging from the simple nearest-neighbour approach adopted here to more sophisticated techniques (e.g. Hoskins and Hodges 2002; Simmonds and Keay 2000). The application of the simple technique used here has yielded results that agree well with those of Hoskins and Hodges (2002).

In this work the temporal variability of cyclone frequency, intensity, size and longevity is analysed together with spatial variations in cyclone occurrence across the North Atlantic. A comparison between the climatologies from both reanalysis data sets is carried out.

2 Data and method

This study uses ECMWF and NCEP reanalysis four times daily mean sea level pressure data covering October 1979 to March 2001. The ECMWF reanalysis data set, known as ERA-15, has been extended from 1994 to 2001 using operational analyses. This strategy to lengthen the available data set from ECMWF has also been employed by Hoskins and Hodges (2002). The same model is used for the reanalysis and the operational analysis, although during the operational phase, updates and improvements were made. Inspection of the time series (see Fig. 5) shows no evidence of discontinuities in the data. Hoskins and Hodges (2002) stated that the use of data produced by different data assimilation systems does not seem to be a major problem at least in the lower troposphere. They found consistent results were obtained from ECMWF, NCEP and GEOS1 reanalyses, all of which used different types of data assimilation. The ECMWF full resolution data are available on a 1.125° × 1.125° grid, much higher resolution than the 2.5° × 2.5° grid provided by NCEP. For simplicity and to ensure the same scale of system is identified for both data sets, the reduced resolution ECMWF data set, archived on a 2.5° × 2.5° latitude-longitude global grid, has been used (available from the British Atmospheric Data Centre).

ECMWF produced the ERA-15 data on a spectral model with a T106 horizontal resolution with 31 levels in the vertical. An intermittent optimal interpolation assimilation scheme was used to interpolate observations to the analysis grid based on modelled temporal and spatial covariances and statistical relationships. The operational data differs with the introduction of 3D (1996–1997) and 4D (1997 →) variational data assimilation and increased horizontal (T213, T319 (1998–2000), T511 (2000 →)) and vertical resolutions (31 to 60 levels from 1999) (Hodges et al. 2003). The NCEP system uses a lower resolution, T62 spectral model with 28 levels in the vertical. Further details of these systems can be found in ECMWF (2001), Gibson et al. (1999) and Kalnay et al. (1996).

Both reanalyses are strongly constrained by the available observations which are assimilated by the respective models. In regions with abundant observations e.g. the Northern Hemisphere, the reanalysis output is less dependant on the model and physical parameterisations than for regions with sparse data coverage e.g. the Southern Hemisphere. This being the case, the two reanalyses data sets analysed here, should yield similar results.

There are various drawbacks to the use of mean sea level pressure (MSLP) data in cyclone detection studies. These include the fact that MSLP is strongly influenced by large spatial scales and strong background flows such as can occur during strong positive NAO phases. This might result in only large scale, slow moving systems being detected (Sinclair 1997). Other variables traditionally used in cyclone detection include geopotential heights (e.g. Sickmoller et al. 2000; Trigo et al. 1999), but these suffer from similar influences (Blender et al. 1997). Vorticity has also been used (e.g. Hoskins and Hodges 2002; Sinclair 1997) but, despite the fact that it is generally less influenced by background flow, this field may be very noisy so that smoothing or reduction of resolution may be necessary (Blender et al. 1997; Sinclair 1997; Sickmoller et al. 2000). For the following reasons, MSLP has been used in this study. First, there is a large body of existing research relevant to the North Atlantic-European sector that has already utilised this variable (e.g. Schinke 1993; WASA 1998; Alexandersson et al. 2000; Gulev et al. 2001). Using gridded and observed MSLP to look at storm occurrences, these studies form a valuable basis for comparison. Second, the Hoskins and Hodges (2002) study investigated the suitability of a number of variables for use in cyclone detection, including MSLP, upper and lower tropospheric height, meridional wind, vorticity and temperature, potential vorticity on 330-K isentropic surface and potential temperature on a PV = 2PVU surface. They found that, in general, all were good indicators of synoptic activity, and that in fact MSLP and 850 hPa vorticity produced similar results although the latter was better at describing smaller-scale systems.

The focus of this comparison is purely on cyclones which develop across the North Atlantic and which therefore have the potential to affect Western Europe. As a result, the study region extends from 80°N–20°N and 80°W–30°E (Fig. 1), encompassing the whole of the North Atlantic, NW Europe and the eastern seaboard of the USA and Canada, a well-established baroclinic zone and cyclogenesis region. The study by Schinke (1993) indicated that approximately 75% of North Atlantic cyclones develop during the winter half of the year (October–March), and here we have chosen to confine our analysis to this period.

The relatively coarse spatial resolution of 2.5° × 2.5° at which the NCEP reanalysis data are available could cause problems in the detection of cyclonic systems (Sinclair 1997). Blender and Schubert (2000) have shown that a reduction in spatial resolution can cause a reduction in cyclone detection and tracking efficiency by 15%. We have to ensure comparability between the NCEP and ECMWF data sets. As NCEP has the coarsest resolution, this determines the resolution at which we must compare the two reanalyses. To ensure that cyclones are detected and tracked as effectively as possible, the highest temporal resolution available (6 hourly) has been used. It is worth noting that Hoskins and Hodges (2002) truncated the T106 ECMWF reanalysis/operational data to T42 (equivalent to ~ 2.8°) and found this suitable for identifying synoptic scale features.

Here cyclones are identified and tracked using an objective system similar to that described by Blender et al. (1997) and Trigo et al. (1999, 2000), although the spatial resolution is much coarser. The detection algorithm identifies the presence of a cyclone as a local mean sea level pressure minimum over a 3 × 3 grid point area. If the pressure at the central point is lower than at the surrounding eight, the central point is classed as a cyclone centre. Most detection procedures require that a set of criteria be met before a cyclone centre is identified. For example, Blender et al. (1997) and Trigo et al. (1999) applied a condition that requires a positive mean gradient to be present in a 1000 × 1000 km^2 region surrounding the central low and Hoskins and Hodges (2002) apply an intensity threshold above which a feature is identified to exist. The method used here applies no criterion other than that MSLP at the central point is lower than at the surrounding eight points. This simple detection and tracking technique ensures that as much of a cyclone's lifecycle is detected as possible.

The tracking method is based on a nearest-neighbour search procedure. The depression trajectory is identified assuming a maximum displacement threshold of 100 km/h, i.e. if the apparent displacement between one time period and the next is greater than 600 km, a separate cyclone system is assumed. Only those cyclones existing for at least one day were retained for analysis.

The radius of each cyclone is determined, as defined by Nielsen and Dole (1992), as the distance between the central position and the nearest col. In other words, the radius is the distance between the centre and the outermost closed isobar. In non-circular systems, the shortest distance to the outermost closed isobar will be measured, and in complex multi-centred systems, a small-scale radius is assigned to each centre. This would lead to an underestimation of the size of the large-scale system within which the multiple centres are contained. To avoid this underestimation, when comparing cyclone size, the maximum radius achieved at any point during a cyclone's lifespan has been used for analysis.

The intensity of each detected cyclone has been categorised based on the Beaufort Scale (BS). This scale is

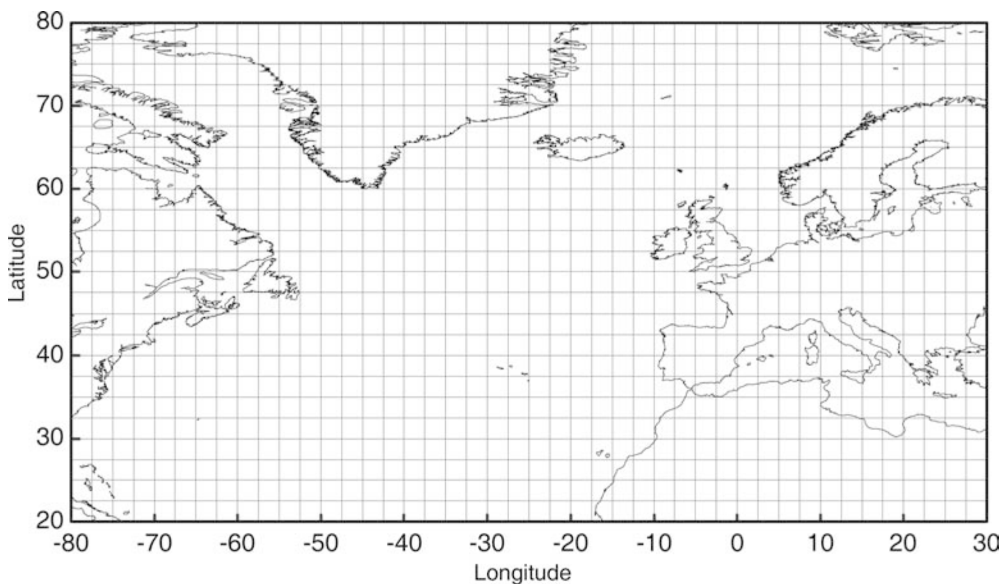

Fig. 1 Map of study area

used because it remains a popular measure of storm/wind strength at the surface (McIlveen 1995) and is still employed by the UK Meterological Office. The scale ranges from zero, calm (wind speed 0–0.2 m/s) to 12, hurricane force (wind speed ≥ 32.7 m/s). The appropriate BS category (BScat) was determined by calculating the gradient wind speed from the radius and pressure gradient achieved at each point in a cyclone lifespan. The maximum gradient wind speed achieved by the cyclone in its lifetime then determines the BScat into which it is placed. In assigning a BScat, the gradient wind speed is used as a proxy for surface wind in preference to the geostrophic wind, because wind speeds in tightly curved troughs, such as are commonly found in mid-latitude low pressure systems, are often subgeostrophic.

3 North Atlantic cyclones

3.1 General characteristics

This section describes the general characteristics of North Atlantic cyclones, as detected by the algorithm used here; their longevity, size and intensity. The results of the two reanalyses are compared. Two intensity thresholds have been selected to enable an investigation of the distribution of all detected low pressure events (BScat 0–12) and of a subset of more intense, damage-producing events (BScat 7 and above). The Association of British Insurers (ABI) (1992) indicate that property damage can occur at wind speeds as low as 16 m/s, which lies within the wind speed range of BScat 7 (13.9–17.1 m/s, near gale).

The majority of detected lows (90.2% of ECMWF and 90.3% of NCEP cyclones) exist for three days or less, the mean being 1.8 days in both data sets (Fig. 2). This average lifespan is shorter than that found by Blender et al. (1997), who excluded cyclones existing for fewer than three days from their study. Nielsen and Dole (1992) found that during a 61 day study (13 January–16 March 1986) across North America to approximately 40°W, the average duration for large-scale events is 83 h (∽3.5 days), whilst small scale systems generally exist for less than 48 h. If the sample is sub-divided based on intensity (BScat 0–6 (those unlikely to create damage) and BScat 7–12 (those able to cause damage)) the results show that for BScat ≤ 6, 80.8% ECMWF and 80.4% NCEP cyclones exist on average for 1.57 and 1.56 days respectively. The remaining cyclones (BScat ≥ 7) persist for an average of 2.71 and 2.76 days. The agreement between the two reanalysis data sets (Fig. 2) is high, with a correlation (R) of 0.99.

Figure 3 shows the size distribution of cyclones detected across the region. Forty-one percent of NCEP and 38% of ECMWF cyclones are 500–1000 km in radius, with the vast majority (98% and 95%, respectively) less than 2000 km in radius. The overall average is ∽1000 km for ECMWF cyclones and ∽900 km for NCEP cyclones. These results compare well with those of Nielsen and Dole (1992) who found that the average radius of travelling cyclones over North America and the western North Atlantic was 875 km. The R-value between the two reanalysis data sets (Fig. 3) is 0.97. Sub-dividing based on intensity shows that BScat 0–6 cyclones have an average maximum radius of 905 km and 780 km for ECMWF and NCEP respectively. For BScat 7–12 these averages increase to 1515 km and 1360 km respectively and again compare well with Nielsen and Dole (1992) who found an average radius of 1500 km for large-scale cyclones.

Figure 4 shows the number of cyclones within each Beaufort Scale category. Most cyclones produce

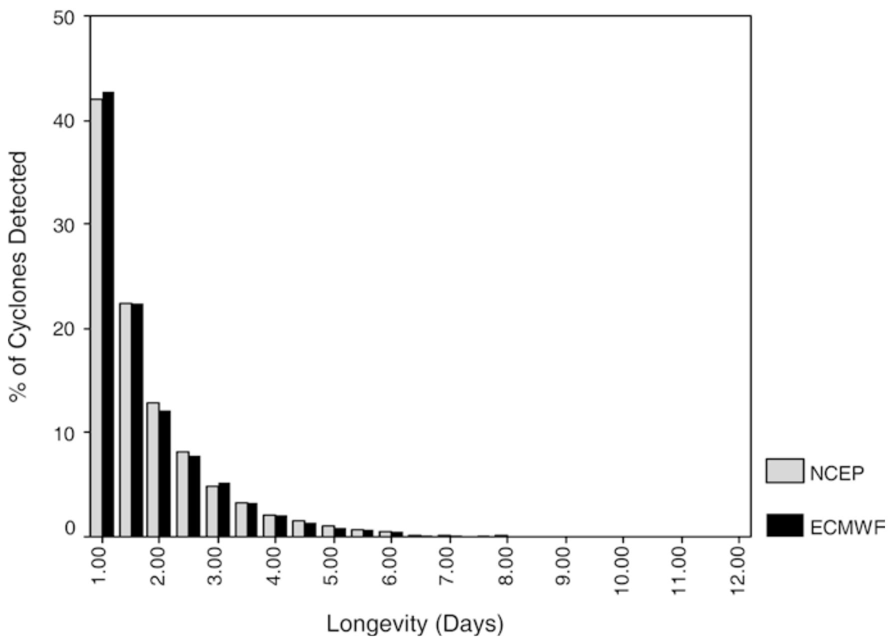

Fig. 2 Percentage of North Atlantic cyclones detected per lifespan category

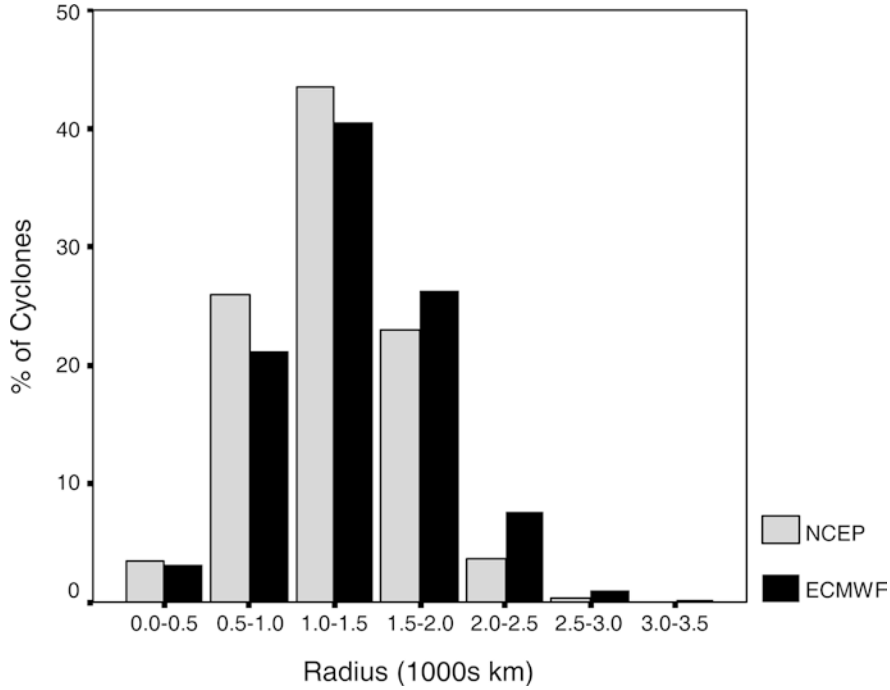

Fig. 3 Maximum radius distribution for all detected cyclones

maximum wind speeds in the range of BScat 3 to 8 (90% for NCEP and 87% for ECMWF). The correlation (*R*) between the two data sets is 0.99. Sub-dividing based on intensity shows that 80% and 81% of cyclones lie within the BScat 0–6 range for NCEP and ECMWF respectively. The majority of these lie within the BScat 3–5 range – 15.6% and 16.9% in BScat 3, 22.7% and 23% in BScat 4 and 20.1% and 19.2% in BScat 5 for NCEP and ECMWF respectively.

The high correlations produced here for duration, size and intensity indicate that both reanalyses replicate these characteristics of North Atlantic cyclones well. The greatest difference between the two datasets is that ECMWF produces a greater number of cyclones in general (14,172 compared to 12,637 for NCEP for BScat 0+ cyclones and 2,717 compared to 2,477 for NCEP for BScat 7+ cyclones during the 22-year study period). This is most likely to be the result of the ECMWF reanalysis data being generated at a higher grid resolution (1.125° × 1.125°).

3.2 Temporal characteristics

The interannual variability in cyclone intensity is shown in Fig. 5. Clear differences emerge between the NCEP

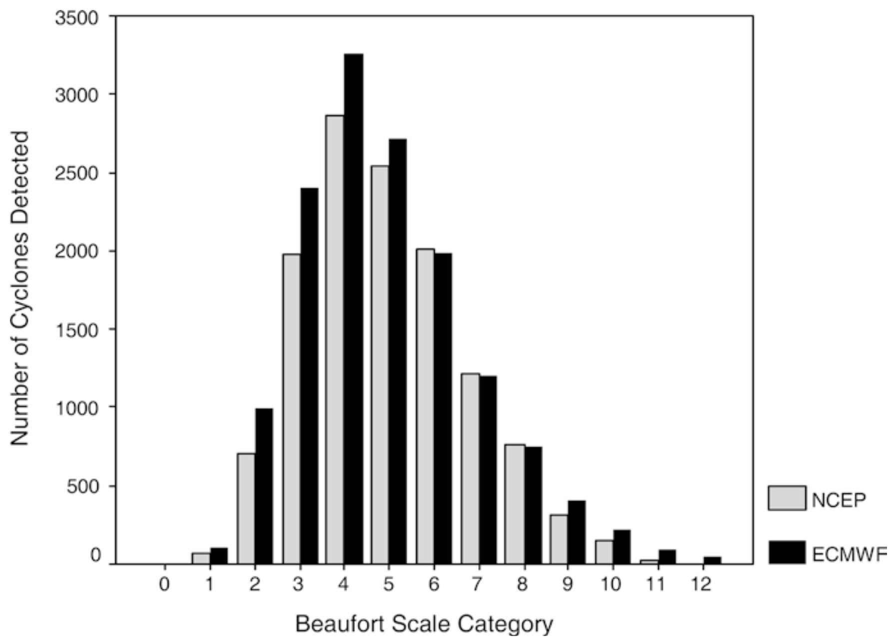

Fig. 4 Number of cyclones detected in each Beaufort Scale category

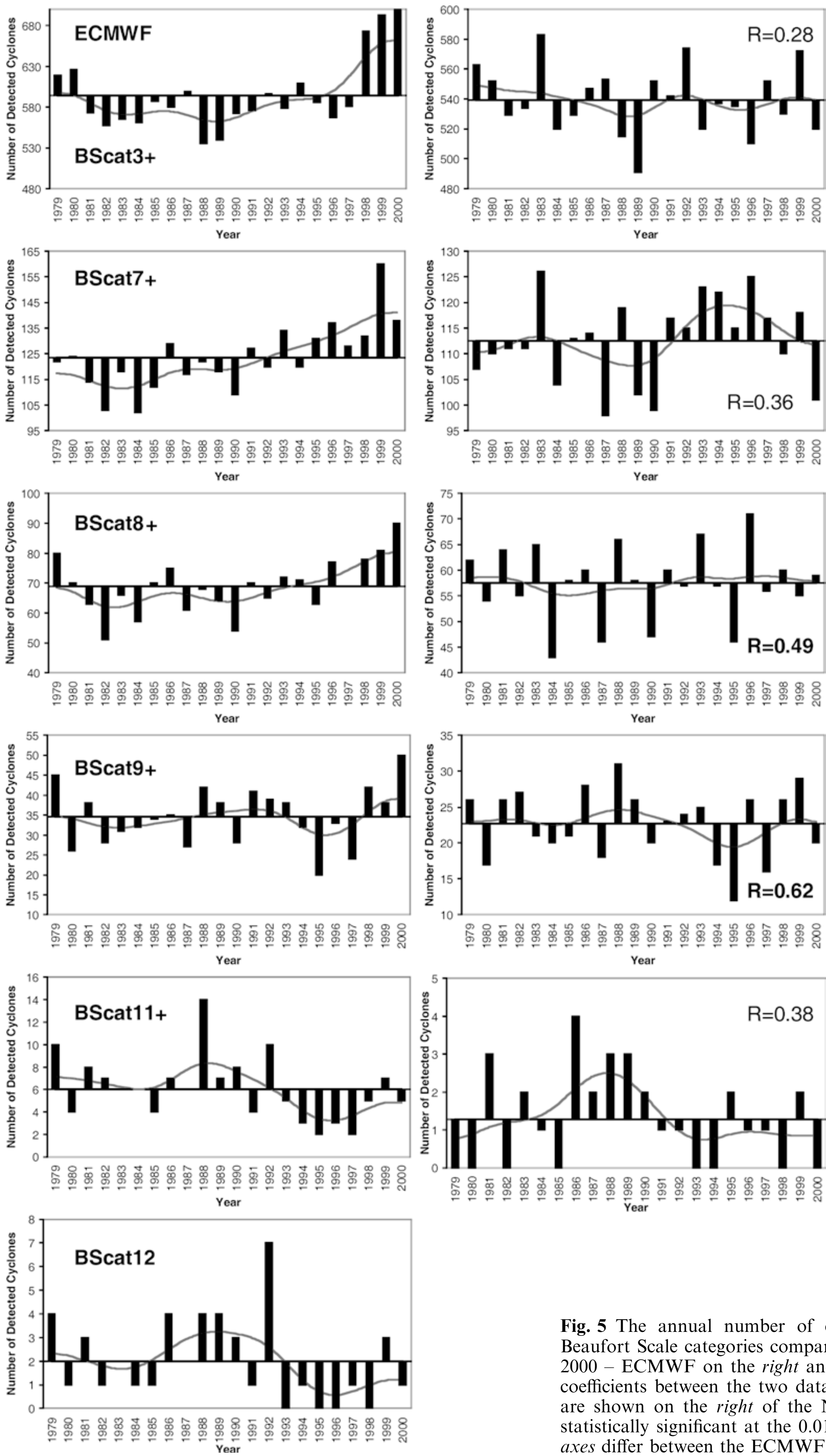

Fig. 5 The annual number of cyclones in and above selected Beaufort Scale categories compared to the mean frequency 1979–2000 – ECMWF on the *right* and NCEP on the *left*. Correlation coefficients between the two data sets for each intensity category are shown on the *right* of the NCEP charts. Those in *bold* are statistically significant at the 0.01 level. Note the *scales* on the *y-axes* differ between the ECMWF and NCEP charts

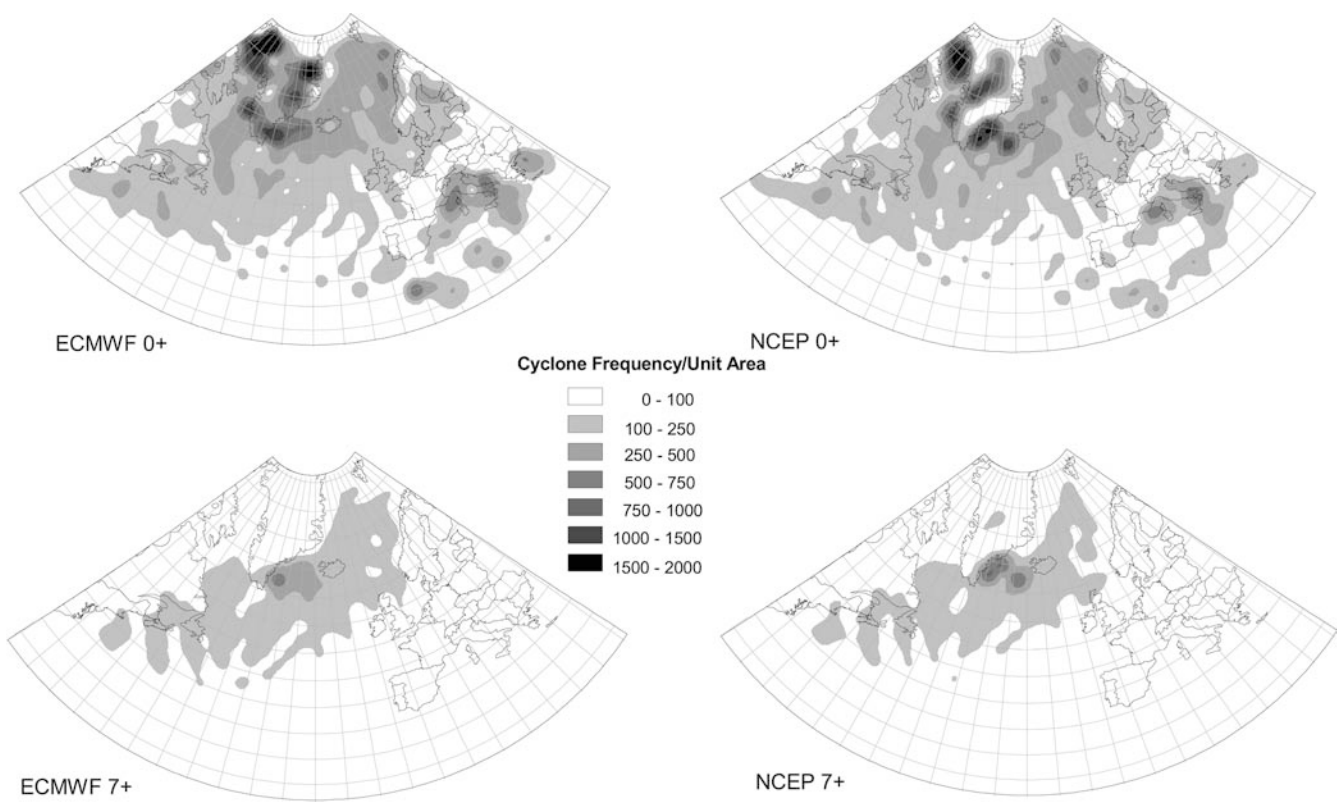

Fig. 6 Cyclone frequency per unit area (~7800 sq km) for different Beaufort Scale categories. ECMWF (*left*), NCEP (*right*)

and ECMWF reanalyses. The objective automated detection and tracking methods are identical for both systems yet ECMWF in all cases produces a greater number of cyclones. The agreement between the number of events detected by the two data sets is poor for all categories below BScat 8. The correlation (given in the upper right hand corner of each NCEP graph in Fig. 5) between the two data sets is statistically significant at BScat 8+, BScat 9+ and BScat 10+ (not shown). The highest correlation is 0.62 for BScat 9 and above. For BScat 12, there are too few NCEP cyclones to calculate a meaningful Pearson correlation coefficient. These results suggest either that the ECMWF reanalyses over-estimates the number of weak and/or very strong systems, or that the NCEP model has a problem simulating these extremes. The latter cause has a greater likelihood of being correct than the former, as will be shown in Section 3.3.

Despite the differences between the two reanalyses, some common trends in frequency can still be identified over the 22-year study period, particularly for the more intense cyclones. The ECMWF reanalyses show an increasing trend in activity throughout the study period for cyclones below BScat 9. The more intense categories (> 8) show a decline in activity from the latter part of the 1980s to the mid-1990s followed by an increasing trend until 2000. This pattern of activity is also replicated in the NCEP data. These results suggest that from 1979 the increase in cyclone activity has been driven by an increase in the weaker cyclones but also include those of BScat 7 and 8 intensity. The more intense cyclones (> 8) contribute to the increase in activity during the last five years of the study period. The general rising trend found throughout the study period supports the findings of the WASA group (1998) and Alexandersson et al. (2000). The overall conclusion from the WASA group was that storminess in the North Atlantic had not increased in recent years beyond the bounds of natural variability experienced over the last 100 years. They also emphasised that investigations of this nature, based on relatively short time periods, cannot definitively conclude that trends are either due to natural variability or are a result of human-induced global warming. Alexandersson et al. (2000) extended the WASA time series to 1998 and showed that, after the peak in activity in the early 1990s, there was a decline in activity, marking the end of the long-term trend in NW European storminess. This study, has shown that the ECMWF and NCEP data supports this decline in activity from the early-1990s identified by Alexandersson et al. (2000), but this is then followed by an increase in activity. However, this increase does not exceed the mean activity levels for the study period.

3.3 Spatial characteristics

A comparison between the NCEP and ECMWF climatologies was carried out with respect to the spatial distribution of BScat 0+ and BScat 7+ cyclone

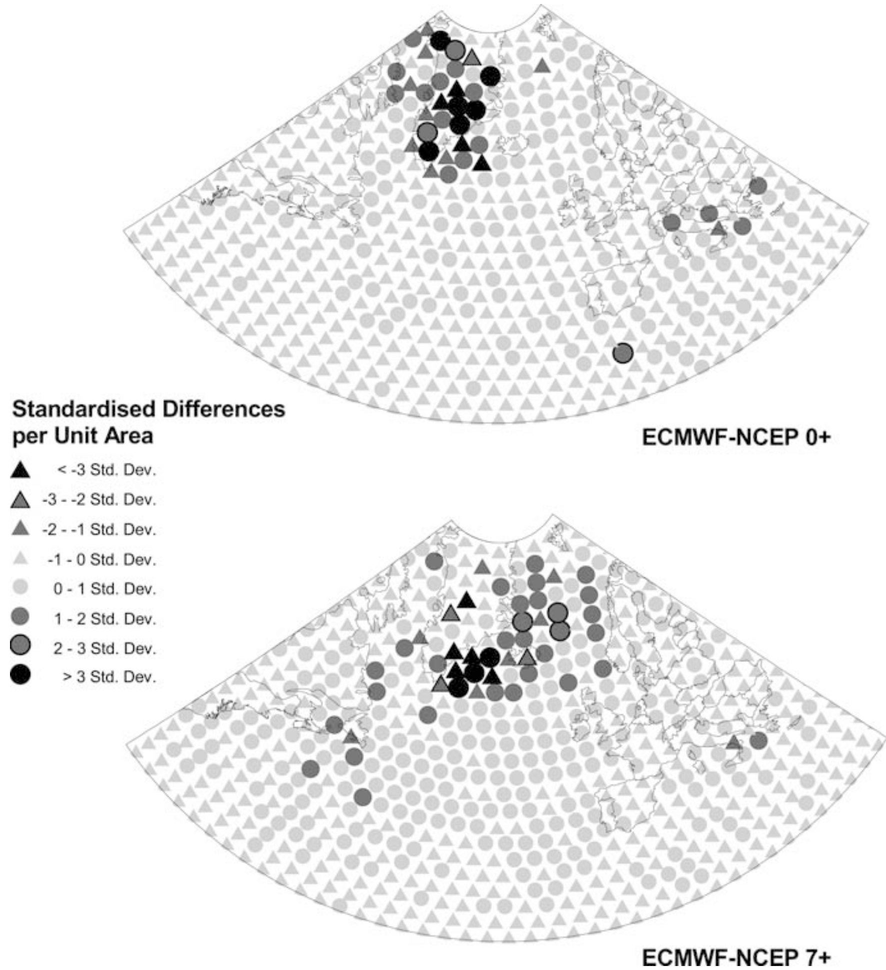

Fig. 7 Standardised cyclone frequency difference plots (ECMWF-NCEP) per unit area for all detected cyclones (*top*) and potentially damage producing cyclones (*bottom*). Standard deviations greater than 2 represent statistically significant differences

occurrences across the study region. The spatial characteristics have been determined using the cyclone tracking algorithm on an equal area grid (∽7800 km^2, the area covered by a 2.5° × 2.5° grid box centred on 20°N). The spatial patterns of cyclone occurrence can only be understood quantitatively on the basis of an equal area grid. The construction of an equal area grid removes some of the biases associated with latitude-longitude and area-weighted cyclone frequency maps, however, bias can still occur (Taylor 1986; Hayden 1981b). An equal area grid encompassing the study area was constructed and the number of 6-hour low pressure centres within each grid box were determined from the 2.5° × 2.5° ECMWF and NCEP climatologies.

Cyclone frequencies per unit area are described by Figs. 6–9. Fig. 6 shows cyclone frequencies for BScat 0+ events (top) and BScat 7+ events (bottom). The area of activity extends from the east coast of the United States to Scandinavia in a southwest/northeast orientation. Several areas of concentrated activity can be identified from both data sets and from both intensity categories. These are located along the Greenland coast. Differences do exist between the two intensity categories. The greatest frequencies for all cyclones are found along the Greenland coast and, in NCEP, extending into the interior. However, for BScat 7+, core activity in both reanalyses lies to the southeast of Greenland and, to a lesser extent, off Newfoundland and Labrador. In the NCEP data, the frequency of the more intense cyclones in the area to the southeast of Greenland is particularly high. It should be noted that these regions of high frequency correspond closely with those areas where BScat7+ cyclones achieve their greatest intensity e.g. Labrador Sea, Denmark Strait and to the north of Scandinavia.

Correlations between the NCEP and ECMWF data sets (Table 1) reveal that the agreement in the spatial patterns is poorest for the BScat 0+ data (R = 0.62) whilst a much higher correlation coefficient of 0.89 is produced at the BScat 7+ level. Figure 7 shows the standardised ECMWF minus NCEP difference plots for BScat 0+ and BScat 7+. The variance between the two reanalyses as expected is greatest at the BScat 0+ level. For all cyclones the greatest differences lie over Greenland and the Atlantic waters off the southeastern Greenland coast. Negative frequency anomalies are located to the southeast of Greenland and across central Greenland indicating that NCEP identifies a greater number of cyclones in these areas. Positive anomalies

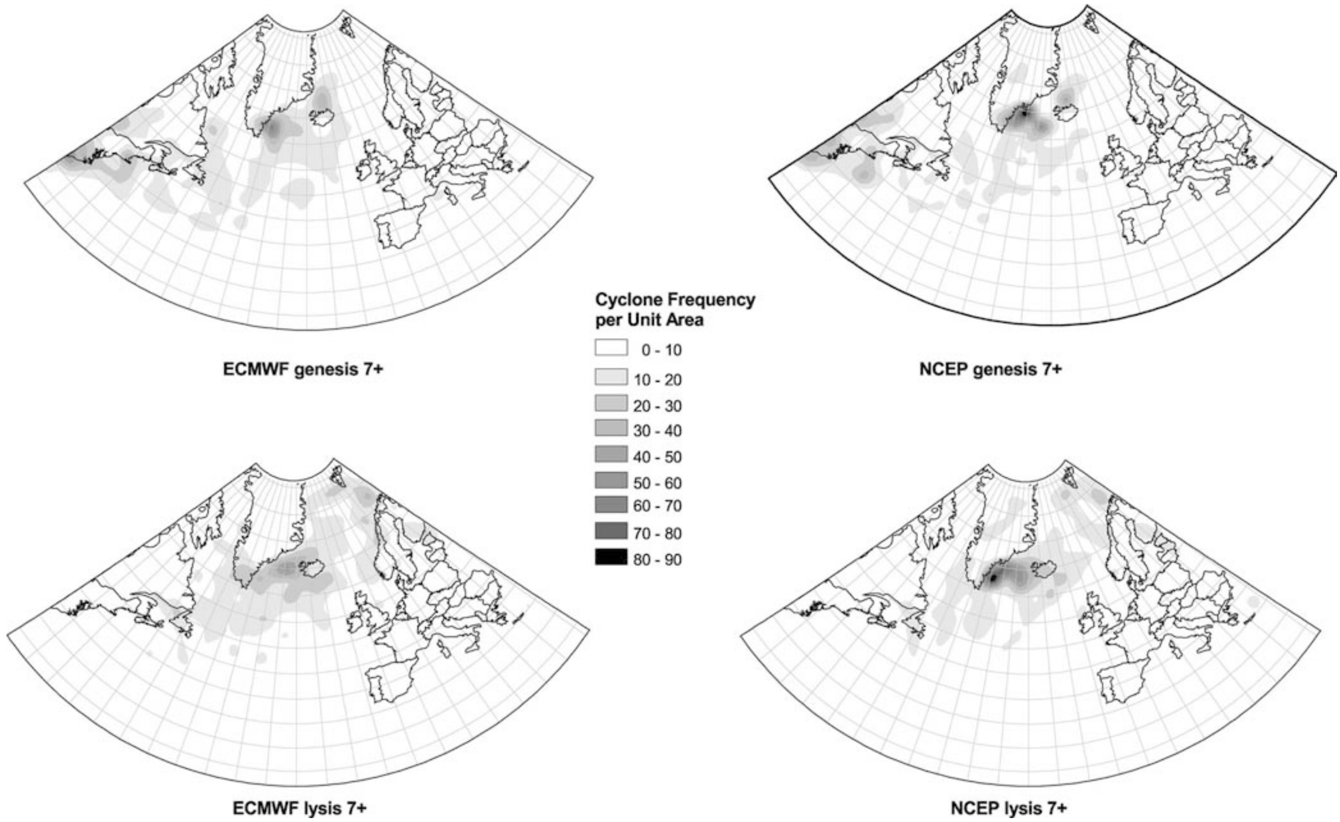

Fig. 8 Cyclogenesis (*top*) and cyclolysis (*bottom*) frequency per unit area for BScat 7+. ECMWF (*left*), NCEP (*right*)

(ECMWF > NCEP) are found over southern, northern and eastern Greenland. There are also substantial differences over the Mediterranean, where the ECMWF reanalysis is identifying a greater number of the smaller scale systems that are characteristic of this area. For BScat 7+ cyclones, the zone of greatest ECMWF-NCEP differences shifts from over Greenland itself, to the offshore to the east and southeast. These differences are mainly positive, indicating that the greatest activity is in the ECMWF data. Jones et al. (2000) carried out a study into the differences between NCEP and UKMO (Jones 1987) sea level pressure data. They found that the largest differences between the two data sets occurred over Greenland in winter (http://www.cru.uea.ac.uk/cru/projects/accord/). Over much of Europe, differences in monthly mean sea level pressure were in the range 1–2 hPa, but over Greenland they were as large as 6–8 hPa, with the NCEP pressures higher than the UKMO pressures. If we accept the UKMO data as correct, and the NCEP winter time pressures as anomalously high, this suggests that the ECMWF-NCEP differences shown in Fig. 7 over Greenland are a result of the NCEP-based cyclone climatologies underestimating the number of cyclones in this region.

The removal of activity located over Greenland reveals an increase in the spatial agreement between ECMWF and NCEP over the remaining domain (Table 1). For all detected cyclones, BSCat0+, the exclusion of systems over Greenland results in an increased correlation of $R = 0.96$. No improvement however, is seen for the higher intensity systems. This indicates that NCEP is producing a higher number of weaker cyclones than ECMWF across Greenland as is suggested in the Jones et al. (2000) study. Over the Greenland region it must be concluded that the greatest difference between the two reanalyses is the simulation of the weaker cyclones around Greenland and must be related to extrapolation to mean sea level, the representation of orography and the higher integration resolution of ECMWF.

The differences between the two reanalyses may be a consequence of the over-simulation of stationary systems particularly in areas of high orography. The removal of stationary systems however, has no noticeable affect on the spatial distribution of systems other than a reduction in overall frequency.

The distribution of cyclogenesis and cyclolysis (frequency/unit area) across the North Atlantic is shown in Fig. 8 for cyclones achieving BScat 7 and above (i.e., with the potential to produce damage). Both ECMWF and NCEP show centres of cyclogenesis along the east coast of the USA, the area to the north and east of Newfoundland and to the southeast of Greenland. The cyclolysis plots again show general agreement between the two datasets, with cyclolysis extending from the USA into Scandinavia with maxima to the southeast of Greenland. The areas of cyclolysis are less spatially extensive, and the core of cyclolysis southeast of

Fig. 9 Cyclogenesis (*left*) and cyclolysis (*right*) standardised frequency difference plots (ECMWF-NCEP) per unit area for all detected cyclones (*top*) and potentially damage producing cyclones (*bottom*).Standard deviations greater than 2 represent statistically significant differences

Greenland is more pronounced in NCEP than in the ECMWF reanalysis.

Figure 9 shows the standardised differences between the ECMWF and NCEP data sets for cyclogenesis and cyclolysis. Positive values indicate a higher frequency in the ECMWF data. Again, the greatest differences, both positive and negative, for BScat 0+ lie over Greenland itself, with positive differences concentrated to the north and east, and negative differences to the west and south. This is true for both cyclogenesis and cyclolysis. For BScat 7+ the greatest differences in cyclogenesis frequency are along the north and east North American coasts (mainly positive) and between Greenland and Iceland (both positive and negative). Cyclolysis differences are greatest along the principal storm track between Greenland and northern Scandinavia, where positive differences dominate (higher frequency in the ECMWF data set).

Table 1 Spatial correlations between ECMWF and NCEP at BScat 0+ and BScat 7+

Intensity category	Spatial correlation
BScat 0+ (including Greenland)	0.62
BScat 7+ (including Greenland)	0.89
BScat 0+ (excluding Greenland)	0.96
BScat 7+ (excluding Greenland)	0.88

4 Comparison of individual tracks

A comparative analysis of five severe storms, which have been well documented in the literature, has been carried out. The tracks are shown in Fig. 10. The actual tracks and central pressures have been taken from articles focusing specifically on these five events and are based on observed as opposed to modelled or forecast data. The references for each storm are found below each of the plots in Fig. 10. Table 2 includes the central pressures for each documented 6-hour time step for the December 1982 and October 1987 storms. Table 3 provides a comparison of general cyclone characteristics for each event as identified from the two reanalysis data sets. These characteristics are minimum central pressure (hPa), longevity (days) and maximum pressure gradient (hPa/100 km). Figure 10 and Table 2 show that neither system performs consistently better than the other. The greatest mismatch between the reanalysis and actual tracks are found for the October 1987 and November 1989 storms. For the October 1987 event this is due to

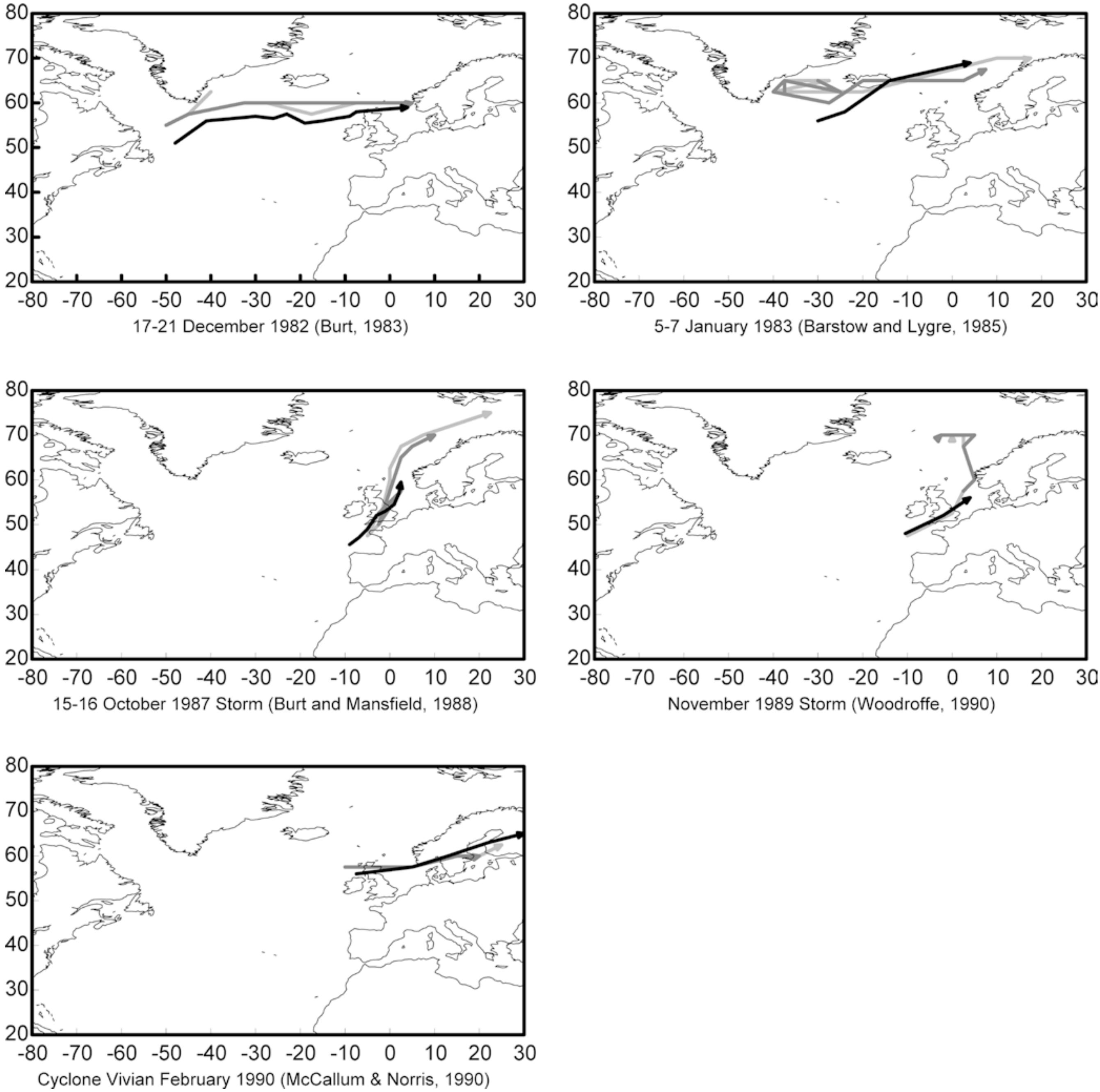

Fig. 10 Comparison between ECMWF (*light grey*), NCEP (*dark grey*) and documented storm tracks (*black*)

the documentation of the track locations and central pressures as the storm affected the UK and crossed into the North Sea only. After this time, approximately 1200 hours on 16th October 1987, the track location and central pressures were not documented. However, forecast data from operational fine-mesh analyses reveals the path of the storm to extend to the north of Sweden by 1800 hours on the 16th October (Meteorological Office 1987). The November 1989 storm reveals that although both reanalyses data sets perform fairly well at replicating the position and central pressures of the majority of intense cyclones, there are still some exceptions. NCEP is particularly poor at replicating the November 1989 cyclone track locations, identifying the start of the track where the actual track decays. Table 3 shows that NCEP cyclones tend to have shorter lifespans, higher minimum central pressures and weaker pressure gradients than those identified from the ECMWF reanalyses.

5 Discussion and conclusions

Objective cyclone climatologies of the North Atlantic have been developed from the ECMWF and NCEP

Table 2 Comparison between ECMWF, NCEP and actual 6-hourly central pressures for the October 1987 and December 1982 storms

Storm	Actual (hPa)	ECMWF (hPa)	NCEP (hPa)
October 1987			
12Z 15/10/87	970	977.1	974.0
18Z 15/10/87	964	965.9	967.9
00Z 16/10/87	953	967.8	969.6
06Z 16/10/87	959	960.5	964.5
12Z 16/10/87	956	959.2	959.2
December 1982			
18Z 17/12/82	990	990.2	990.9
00Z 18/12/82	984	983.2	986.7
06Z 18/12/82	964	969.9	974.3
12Z 18/12/82	949	952.3	961.2
18Z 18/12/82	946	941.8	945.3
00Z 19/12/82	937	937.2	941.0
06Z 19/12/82	936	939.8	937.9
12Z 19/12/82	931	939.6	938.3
18Z 19/12/82	932	939.2	937.7
00Z 20/12/82	934	939.3	938.5
06Z 20/12/82	935	941.6	941.2
12Z 20/12/82	942	946.6	945.7

Table 3 Comparison between ECMWF and NCEP general cyclone characteristics

Storm	Data set	Minimum. central pressure	Lifespan	Maximum. pressure gradient
December 1982	ECMWF	937.2 hPa	5.25 days	6.11 hPa/100 km
	NCEP	937.7 hPa	4.75 days	5.20 hPa/100 km
January 1983	ECMWF	930.0 hPa	3.50 days	5.31 hPa/100 km
	NCEP	933.9 hPa	3.50 days	3.99 hPa/100 km
October 1987	ECMWF	959.2 hPa	3.25 days	3.54 hPa/100 km
	NCEP	959.2 hPa	3.75 days	3.57 hPa/100 km
November 1989	ECMWF	985.5 hPa	3.50 days	3.03 hPa/100 km
	NCEP	986.8 hPa	2.75 days	2.78 hPa/100 km
February 1990	ECMWF	942.5 hPa	2.50 days	3.28 hPa/100 km
	NCEP	943.0 hPa	2.50 days	3.35 hPa/100 km

reanalyses using a relatively simple automated detection and tracking algorithm. From these climatologies a direct and objective comparison of the performance of the two systems has been carried out. Both reanalyses successfully identify the well-known regions of cyclogenesis and cyclolysis and also the characteristics of general cyclone activity across the North Atlantic. No persistent trend in intensity is identifiable over the 22-year study period. However, the 1980s to early 1990s were characterised by an increase in the number of more intense events (BScat 7+). The dominant North Atlantic cyclone track is orientated along a southwest/northeast axis extending from the east coast of the USA to the area north of Scandinavia. The main cyclone activity areas are concentrated along the east coast of the USA, to the northeast of Newfoundland and to the southeast of Greenland, where cyclogenesis is concentrated. Cyclolysis is concentrated to the southeast of Greenland and extends from the east coast of the USA along the Scandinavian coast and into the Baltic States, as well as to the west of Spitzbergen.

There are two principal differences between the NCEP and ECMWF data sets. The first is that, over Greenland, NCEP has many fewer cyclone events than ECMWF. This appears to be related to excessively high sea level pressure in NCEP at this location. The second is that the ECMWF data produces more occurrences of very weak and very strong cyclones than NCEP. This is probably related to the spatial integration resolution and the use of subgrid-scale orographic parameterisation in ECMWF compared to mean orography utilised in NCEP. Hodges et al. (2003) noted that the difference in the orography parameters is more likely to explain the difference in the number of weak cyclones around orographic regions than the different methods of extrapolation.

In general, although the two reanalysis systems differ, it is difficult to attribute the differences in cyclone climatologies to any one particular aspect. Although resolution plays an important part, extrapolation methods used are probably also important particularly around areas of orography e.g. Greenland, as is the representation of orography within the reanalysis systems. These differences arise not only from the structures of the two data assimilation systems (described in Sect. 2), but also in the choices made regarding the data inputs to these systems. Differences exist in the parameterisations employed; for example, the cumulus parameterisation in the NCEP system is based on a simplified Arakawa-Schubert scheme (Pan and Wu 1994) whereas ECMWF employ the scheme developed by Tiedtke (1989). Furthermore, the input data sets are not identical, although a deliberate decision was made to standardise for a single year, 1979. As an example, snow cover in the NCEP reanalyses is based on satellite data from NESDIS, whereas ECMWF snow cover is derived from station observations of observed snowfall and snow depth at each time step. The quite fundamental contrasts between the two reanalyses regarding physical parameterisations, input observations, extrapolation techniques and the spatial integration resolution must be responsible for the differences in cyclone climatologies found in this work.

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